# Application of passive absorbers for improving the performance of the Fermilab Muon g-2 Experiment

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Accelerator Physics and Technology Seminar, Fermilab (virtual)

9 June 2020

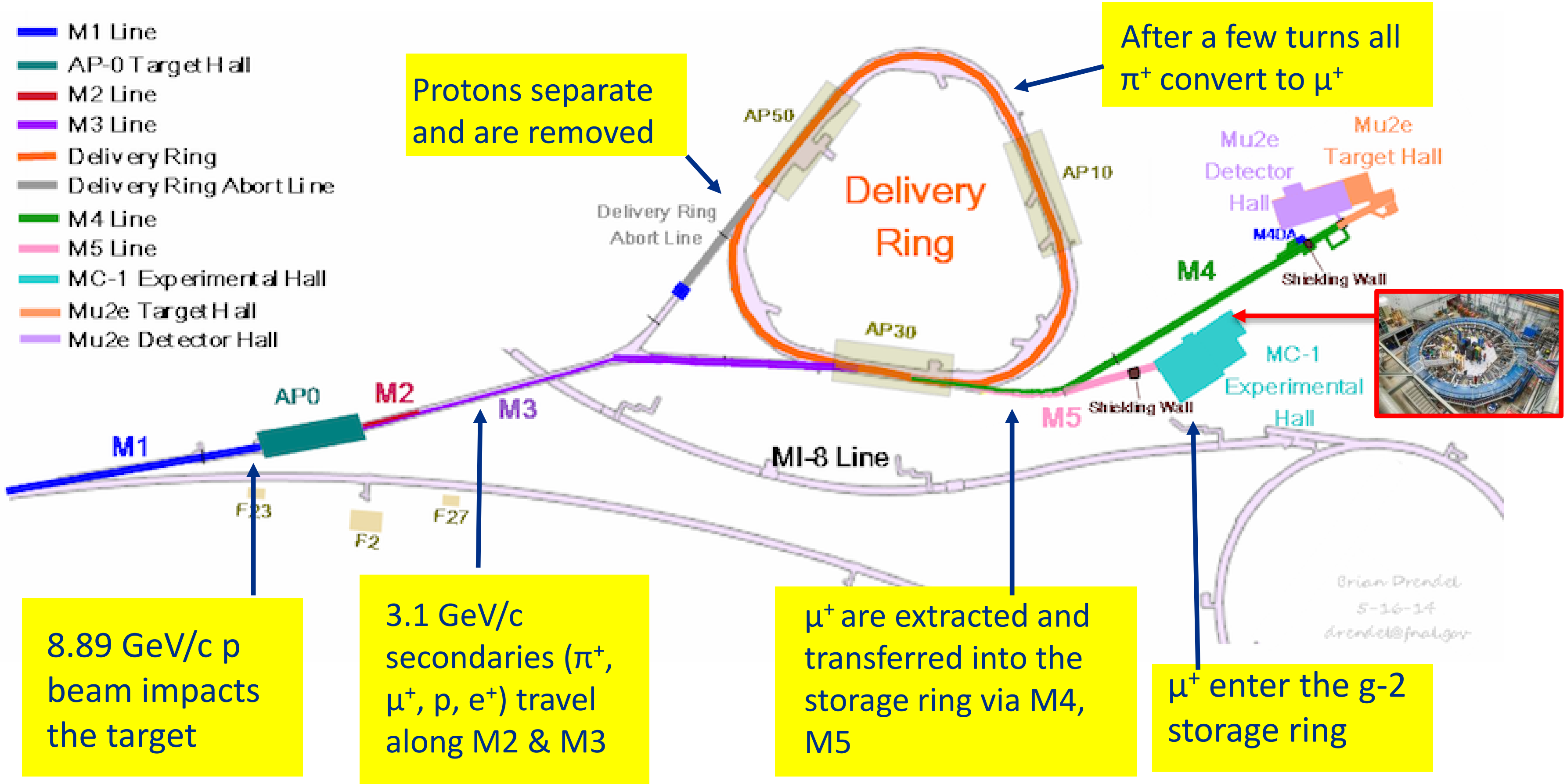
# Outline

- Overview of the Fermilab Muon Campus
- Overview of the Muon g-2 Experiment
- A concept for increasing muon beam intensity with passive absorbers
  - Description of the concept
  - Predictions from simulations
  - Operational experience in the Muon Campus
- Future work

# Motivation

- In the next decade Fermilab will host two world-class precision science experiments:
  - The **Muon g-2 experiment** will determine with high precision the anomalous magnetic moment of the muon.
  - The **Mu2e experiment** will improve the sensitivity on the search for a neutrinoless conversion of a muon to an electron.
- A dedicated accelerator facility to provide beams to both experiments has been designed and constructed at Fermilab
- The Muon g-2 experiment precedes the Mu2e experiment
- In this talk, I will discuss and demonstrate a technique for enhancing the muon intensity of the Muon g-2 Experiment

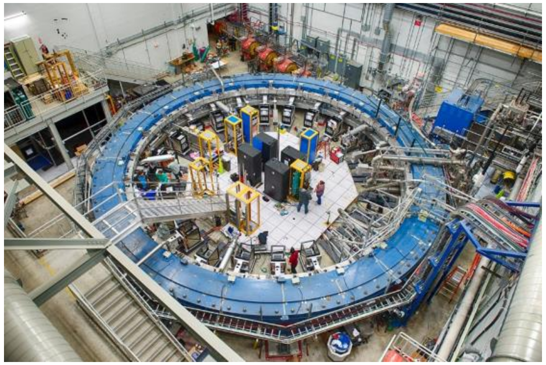
# Muon Campus layout

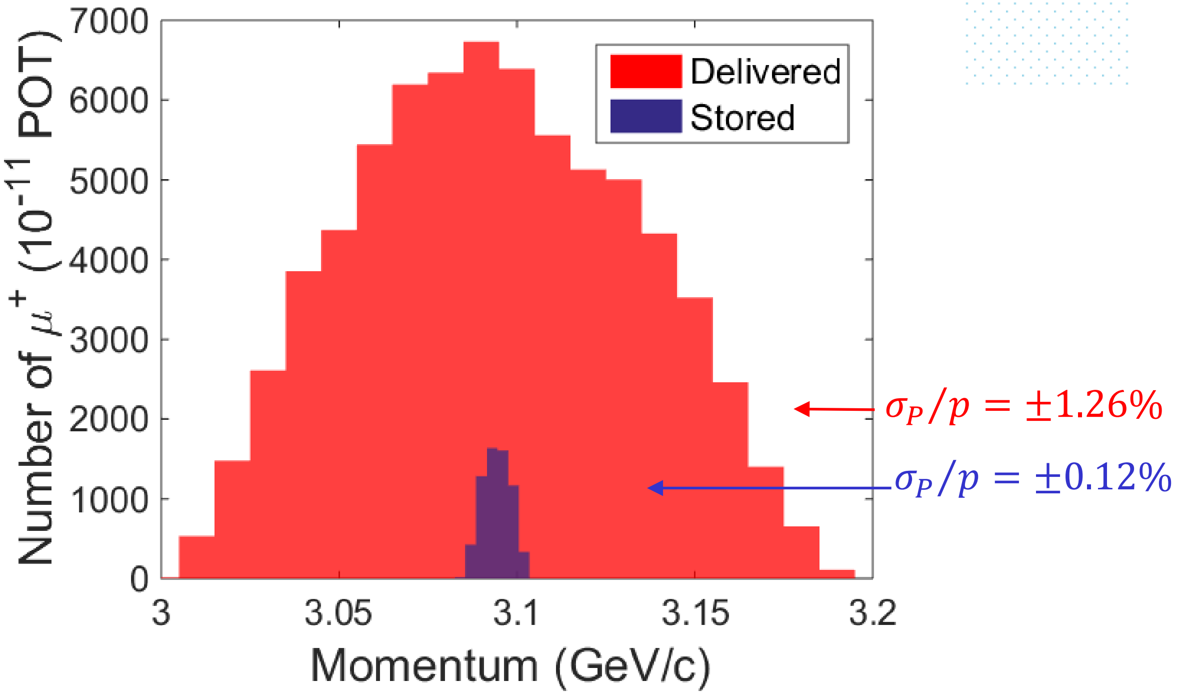



- The delivered muon beam is free of protons and pions, which created a major background in the BNL experiment

# Delivered beam momentum distribution

- The beam delivered to the storage ring of the Muon g-2 Experiment has a rms momentum spread of ~1.3%
- The ring accepts muons within ~0.1% of the magic momentum (~3.1 GeV/c) only. Nearly 90% of the incoming beam is lost.





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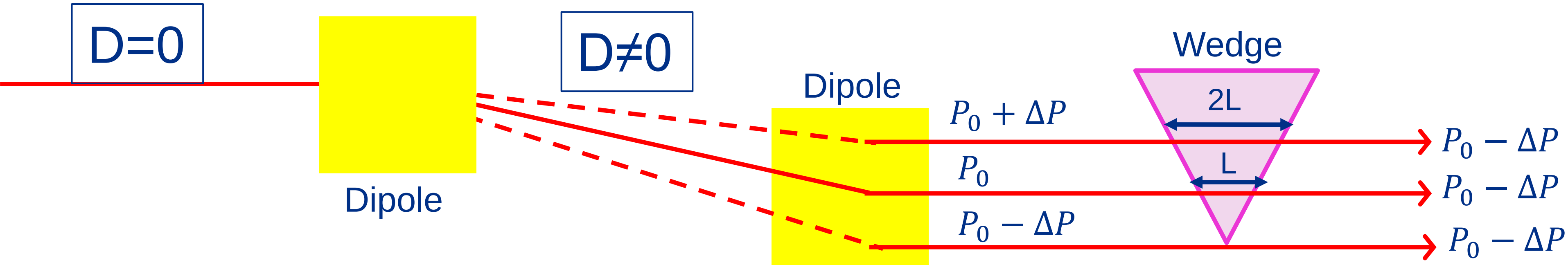
# Proposed improvement strategy

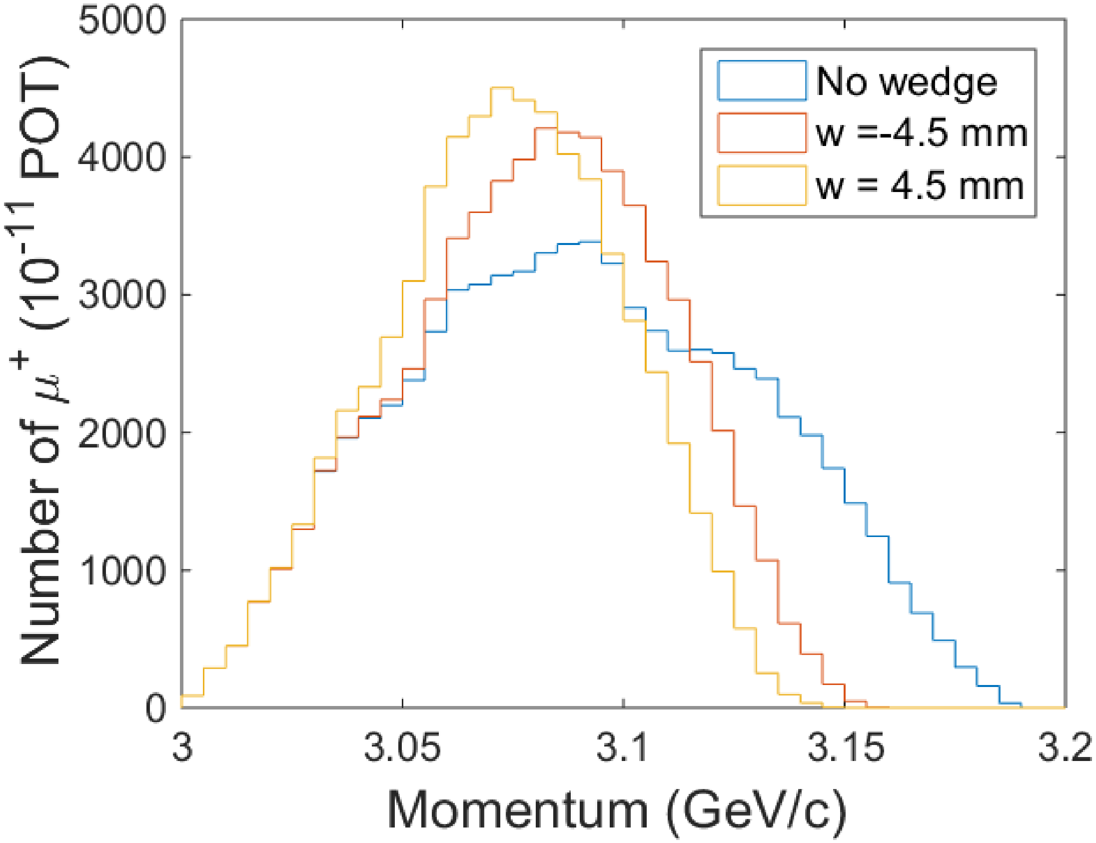


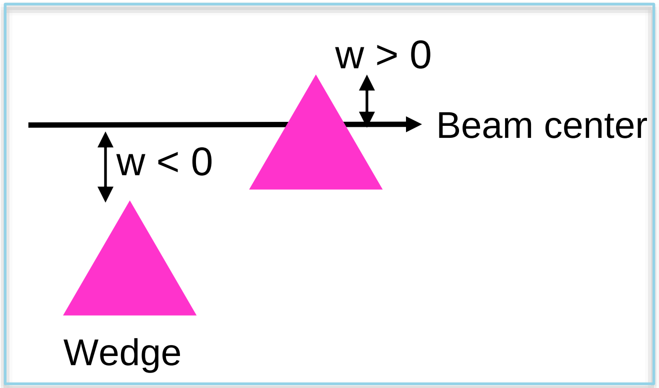
- First separate particles by momentum by guiding them into a dispersive area
- Then, pass the beam through a wedge absorber
- With a properly designed wedge, high-energy muons will lose more energy than low-energy ones. As a result, the overall energy spread of the beam is reduced
- Through Fermilab's LDRD program we have been awarded a grant to design, install and test a wedge in the Muon Campus



# Simulation of the concept

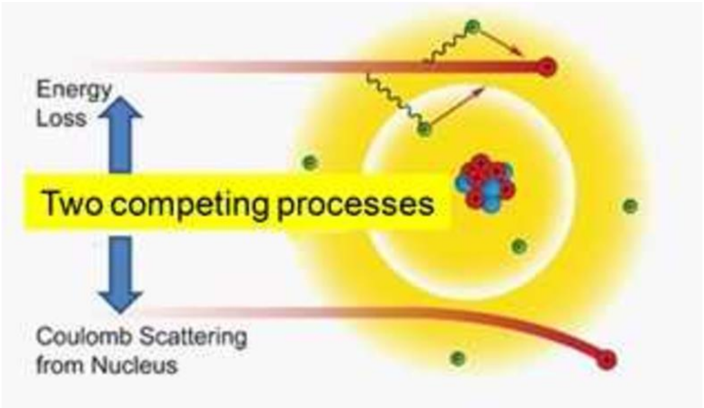
- Simulations of the wedge concept along the Fermilab Muon Campus revealed that a wedge can increase the number of stored muons for the Muon g-2 Experiment



# Requirements

- Mechanisms involved in the process:
  - Energy loss (contraction)
  - Multiple Coulomb scattering (expansion)
  - Energy straggling (expansion)
- We require materials with:
  - Large energy loss term
  - Large radiation length
- Beamline location with:
  - Small beta function
  - Large dispersion

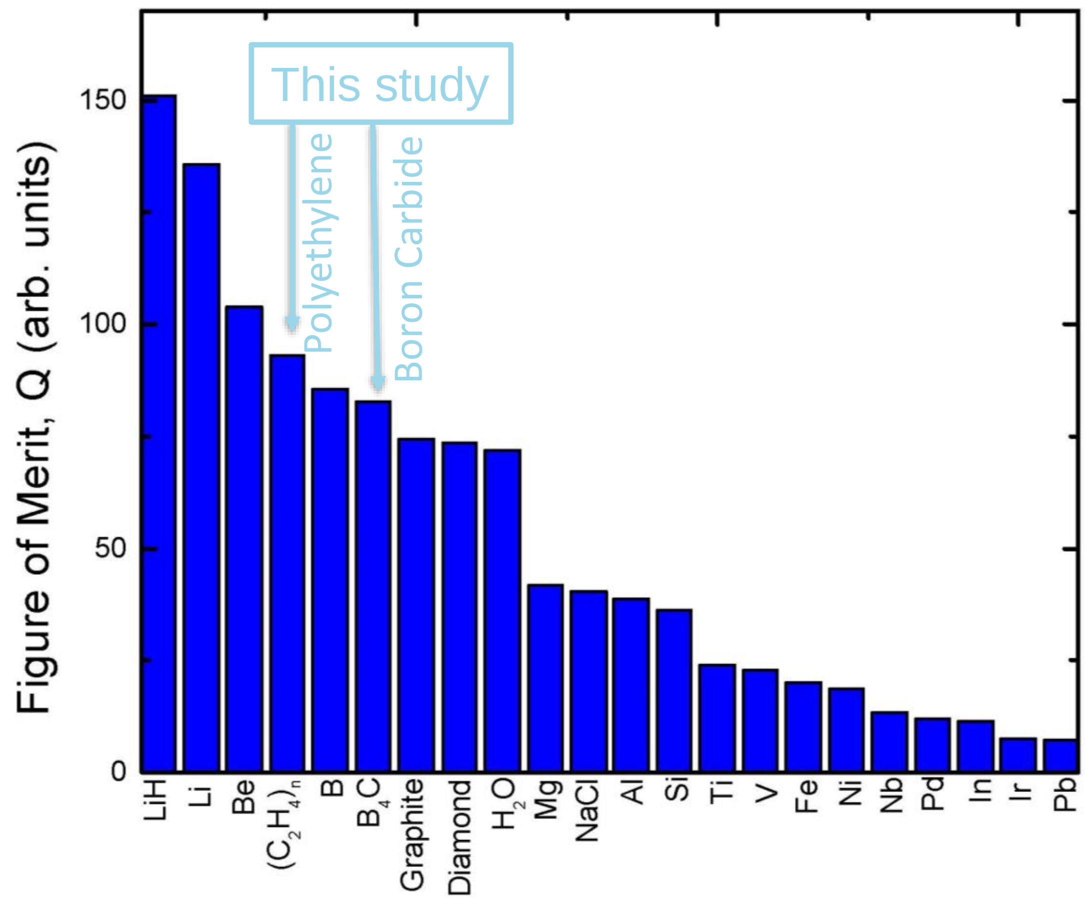


# Choice of material

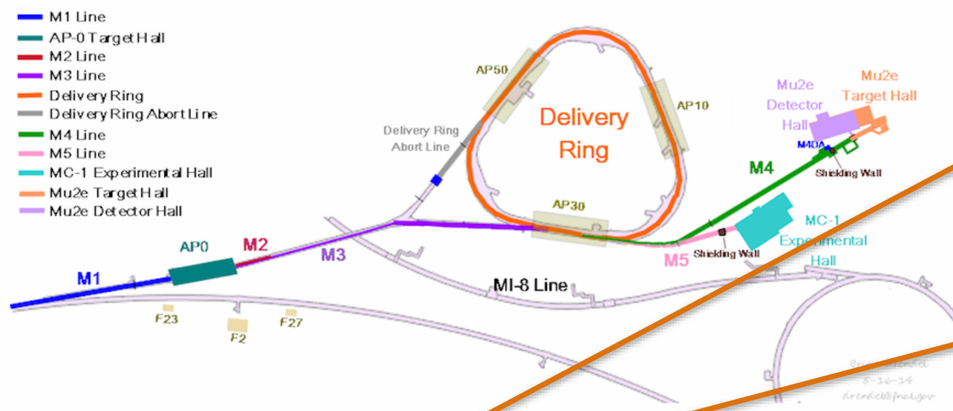
- A figure of merit for each material can be obtained by taking the product of it’s energy-loss and radiation length terms

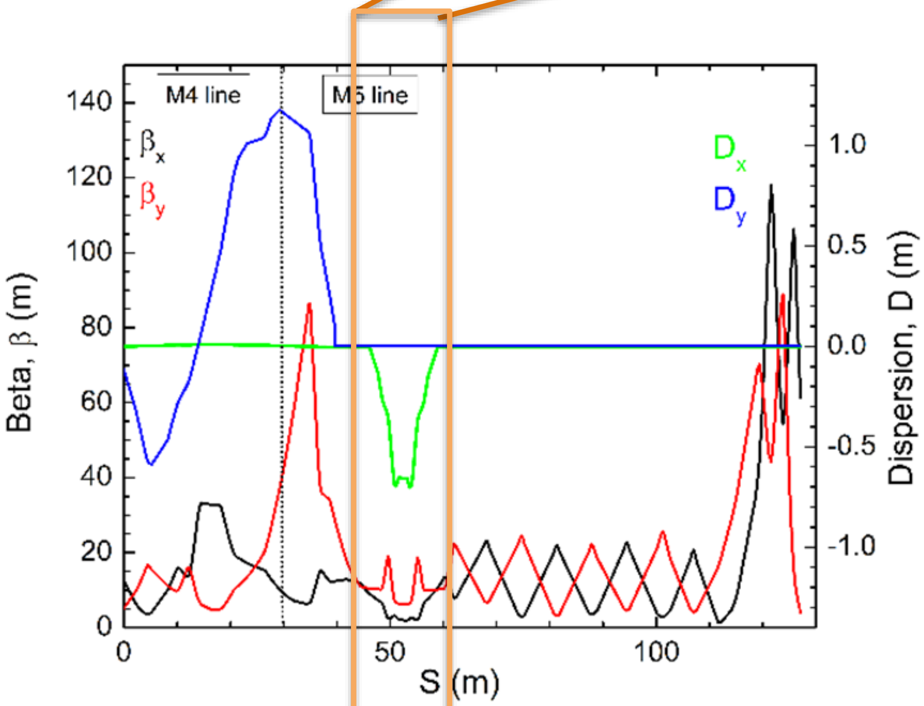
Boron Carbide ($B_4C$)

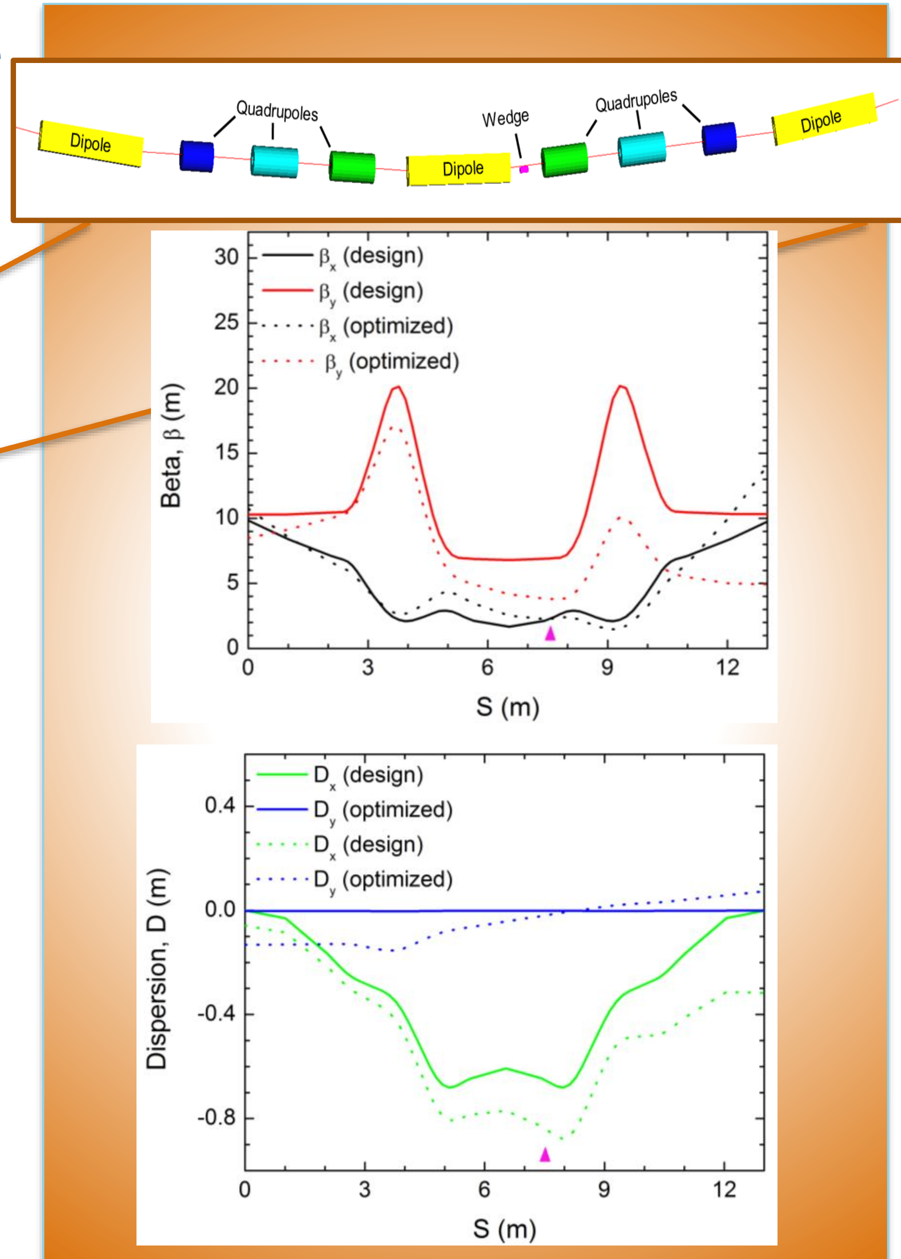
| Quantity | Value | Units |
|---|---|---|
| <Z/A> | | |
| Specific gravity | | |
| Mean excitation energy | | |
| Minimum ionization | 4.157 | MeV cm$^{-1}$ |
| Nuclear collision length | 23.12 | cm |
| Nuclear interaction length | 33.27 | cm |
| Pion collision length | 33.92 | cm |
| Pion interaction length | 46.04 | cm |
| Radiation length | 19.89 | cm |
| Critical energy | 88.08 | MeV (for $e^+$) |
| Molière radius | 4.659 | cm |
| Plasma energy $\hbar\omega_p$ | | |
| Muon critical energy | | |



# Choice of location: M5 line

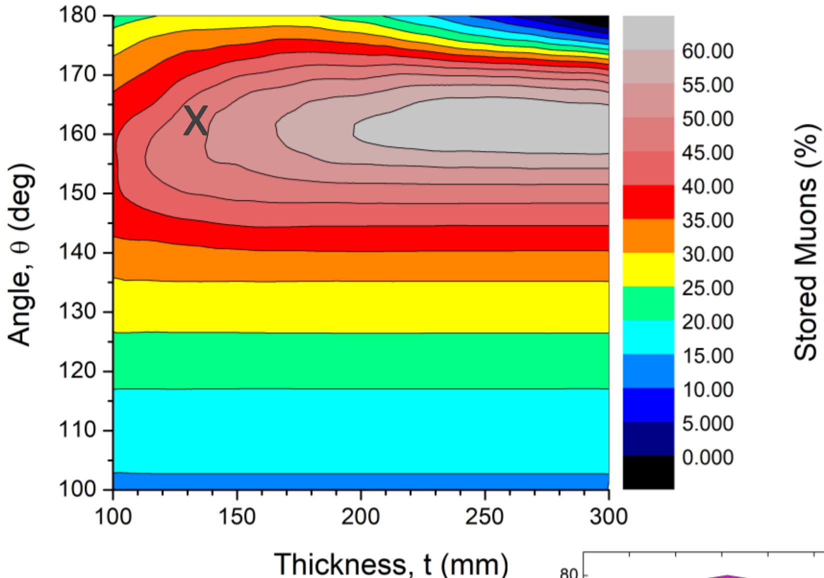


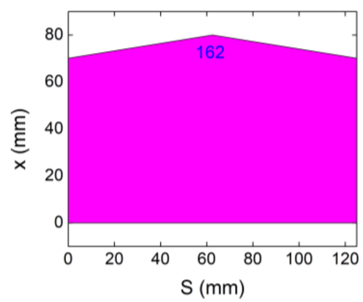



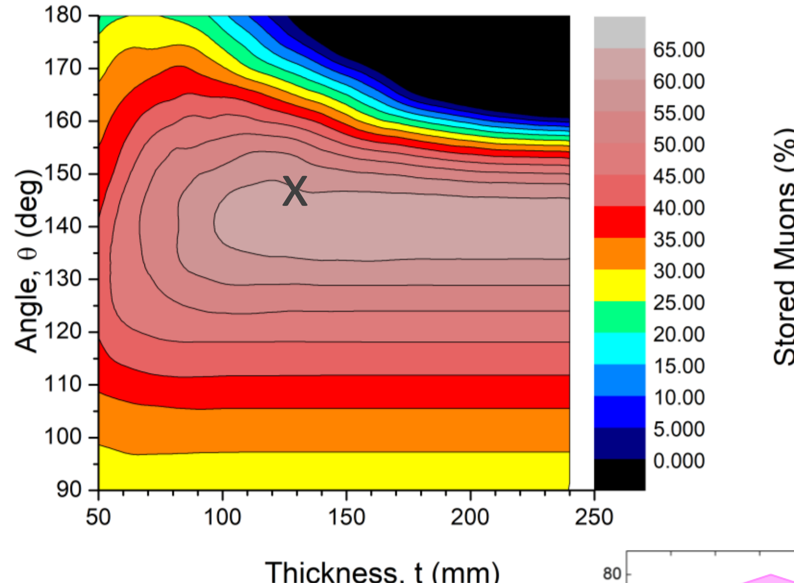
# Choice of geometry

- Optimum wedge geometry was studied with a fast Monte Carlo program
- Space restrictions limit the allowable wedge length to 130 mm

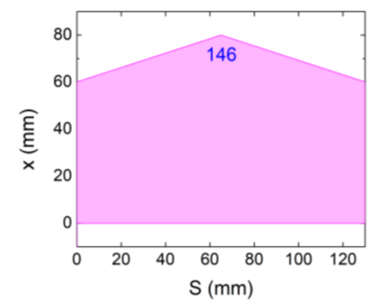



Polyethylene



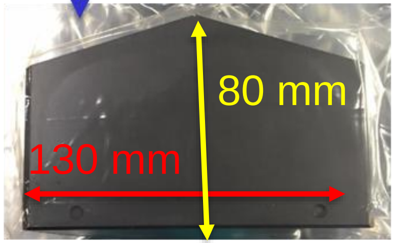

Boron Carbide



# Fabrication and installation progress (1)

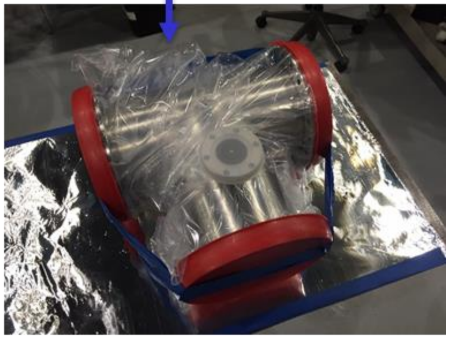
Polyethylene wedge

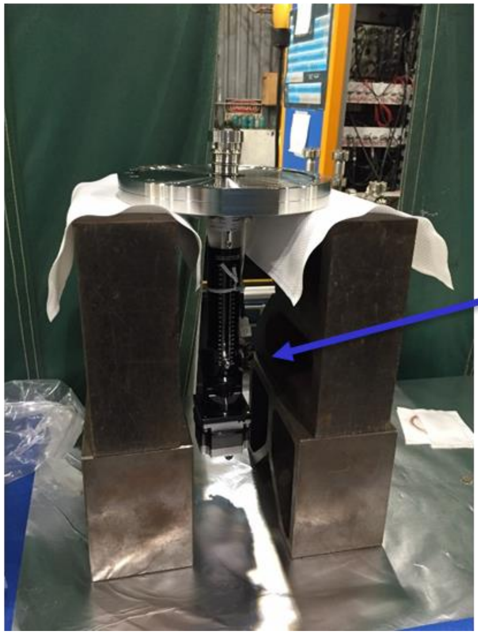
Boron Carbide wedge




New power supplies for downstream optical matching

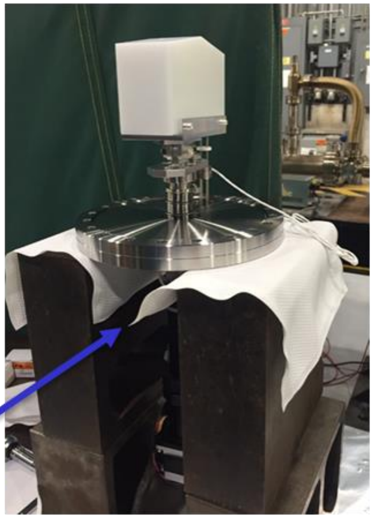
Wedge housing



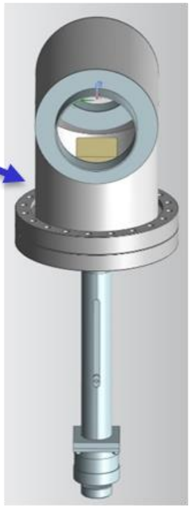


Wedge insertion actuator with submillimeter precision

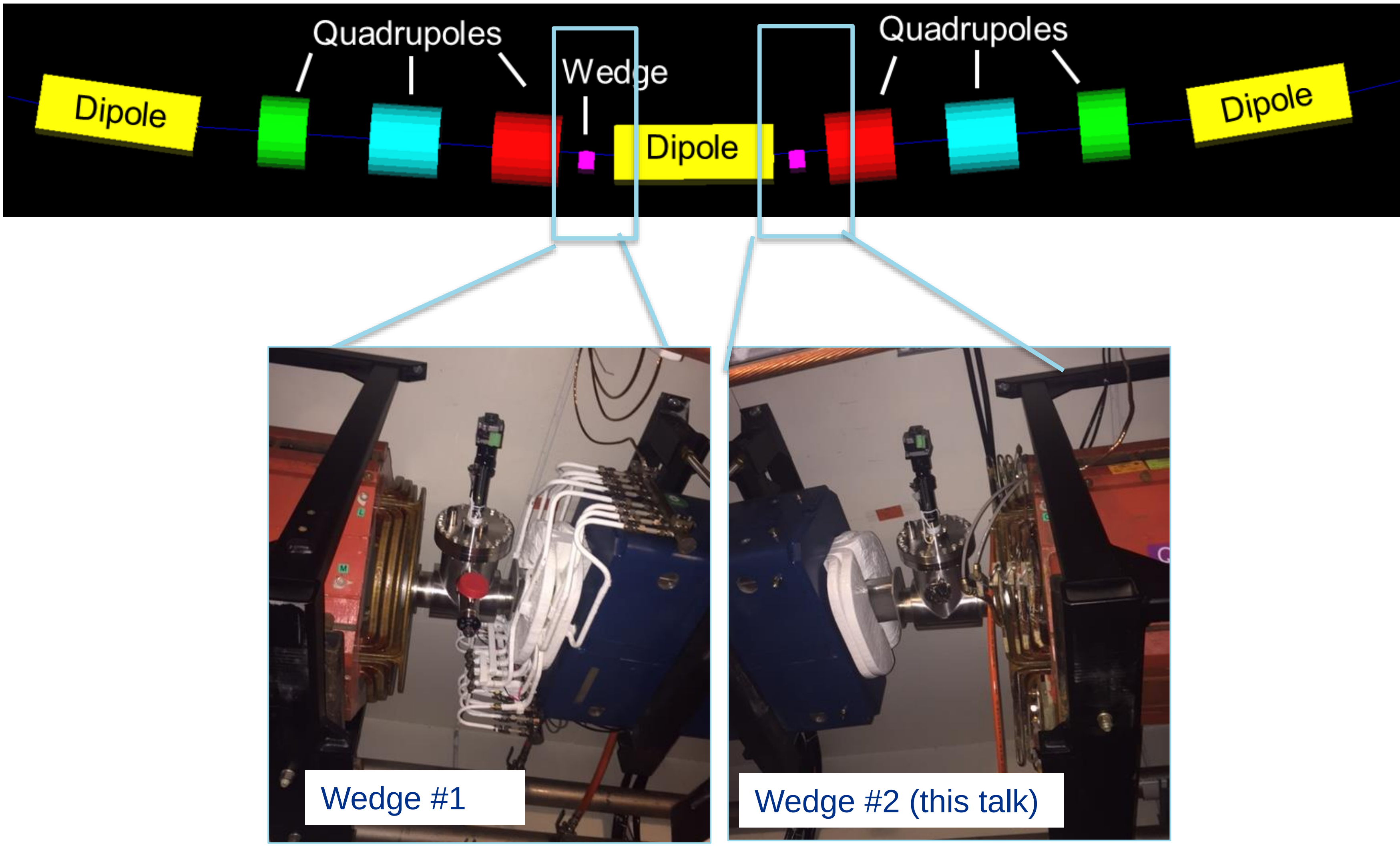
Motion-control tests



Design of complete mechanical assembly



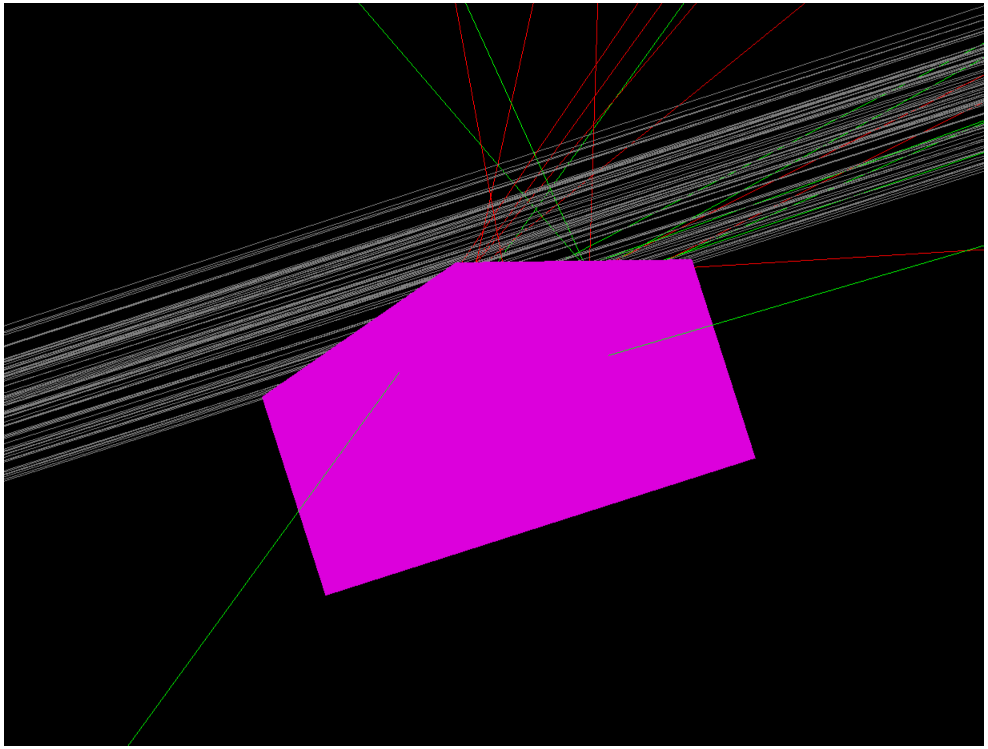
# Fabrication and installation progress (2)



# Simulated trajectories

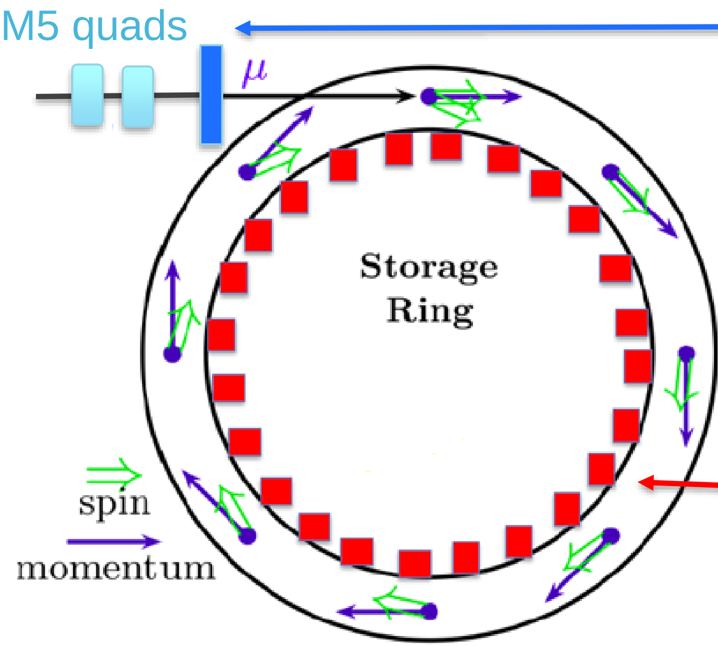
- Beam wedge covers roughly half of the beam
- The majority of beam-material interaction happens near the wedge apex

| Parameter | Value at wedge |
|---|---|
| Dispersion, $D_x$ | 0.85 m |
| Beta, $\beta_x$ | 2.3 m |
| Beta, $\beta_y$ | 3.8 m |
| Emittance rms, $\varepsilon$ | 12.0 µm |
| Sigma, $\sigma_x$ | 10.0 mm |



# Measuring Technique

- We measure beam intensity at two locations: (1) upstream of ring injection, and (2) inside the ring after thousand of turns
- Calorimeters measure only muons that fit within the ring's momentum acceptance. As a result this value provides a key parameter that governs the wedge performance.

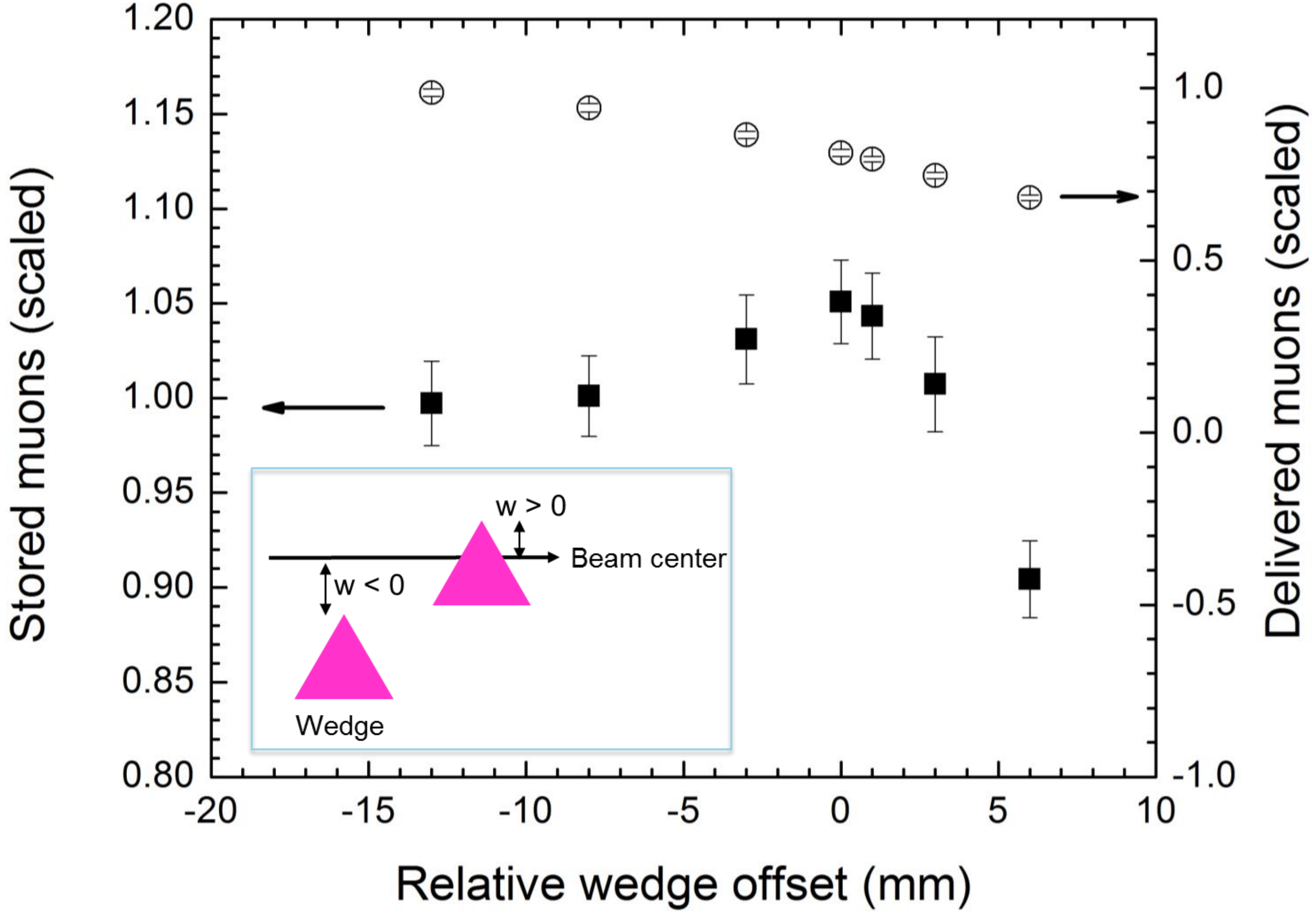



**Ion Chamber**: Is UPSTREAM the storage ring entrance. Measures TOTAL intensity

**Calorimeters**: Is INSIDE the storage ring. Measures muons WITHIN ITS ~0.1% acceptance.

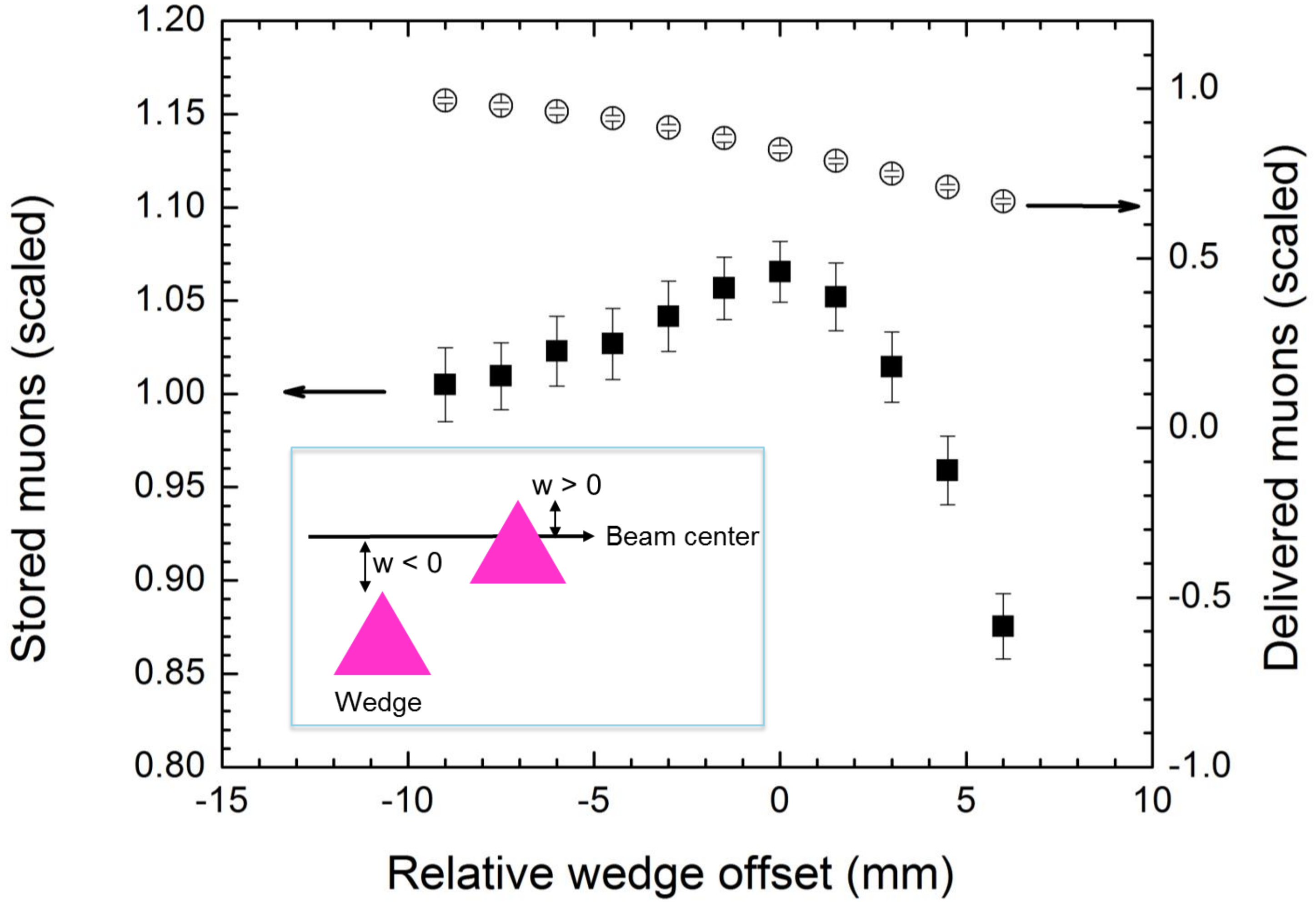
# Test with a Polyethylene wedge

- A polyethylene wedge provided a 5% gain in stored muons



# Test with a Boron Carbide wedge

- A boron carbide wedge provided a 7% gain in stored muons



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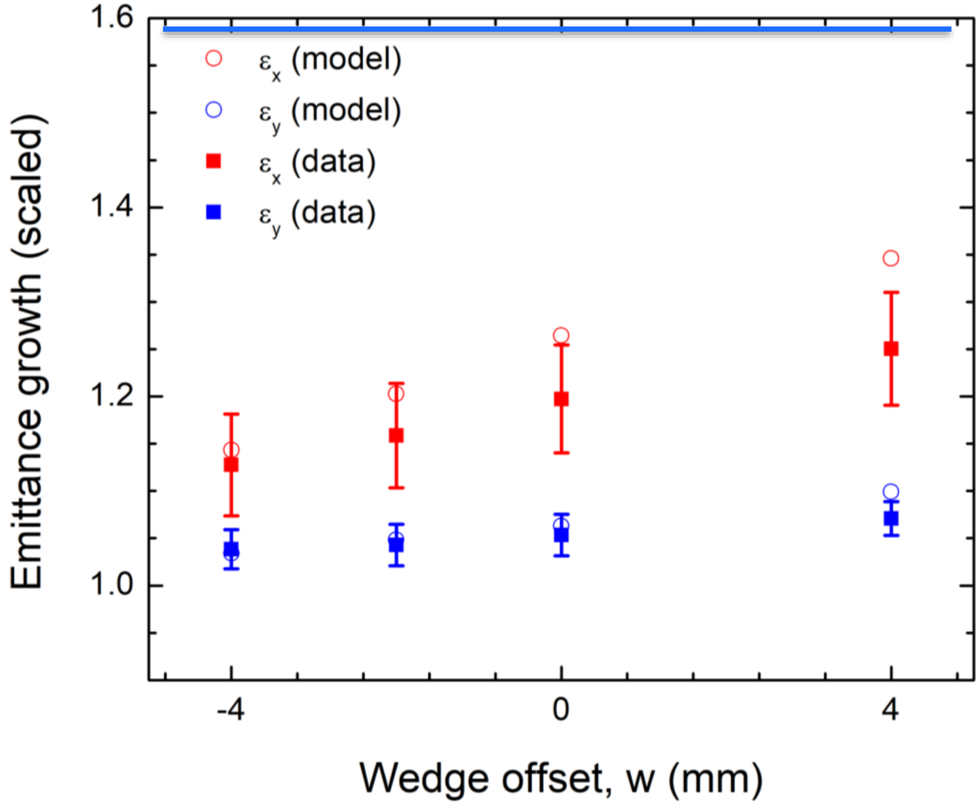
# Emittance growth

- While the momentum spread reduces, the transverse emittance grows as a result of emittance exchange and scattering

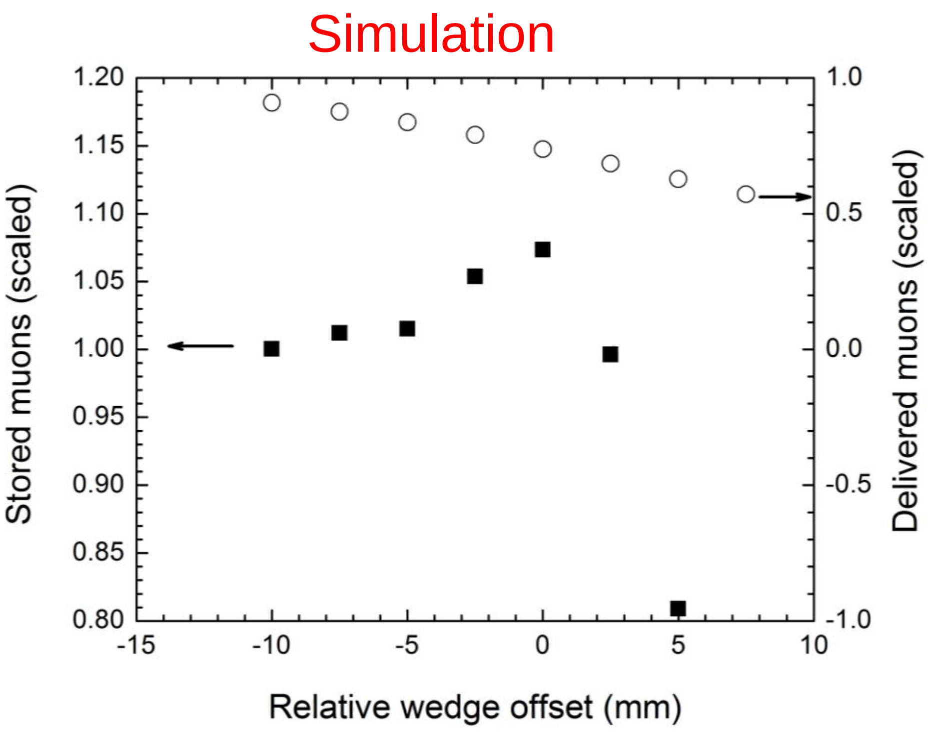


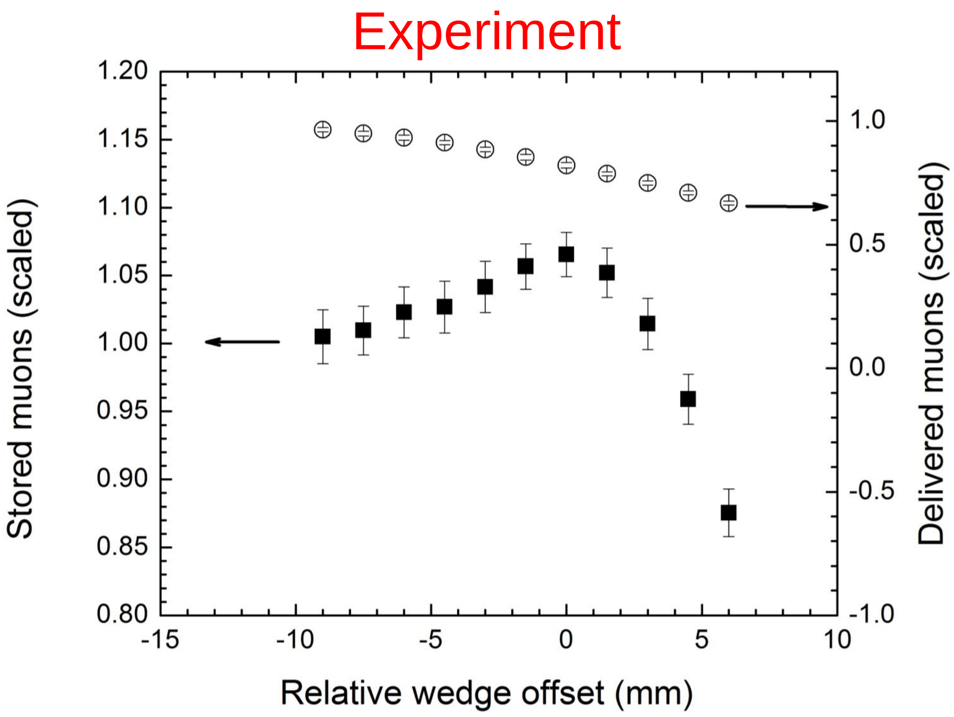

Maximum allowable growth storage ring (y)=1.6

Maximum allowable growth storage ring (x) = 3.6

# Simulation vs Experiment: Storage Ring

- The agreement between simulation and experiment is good



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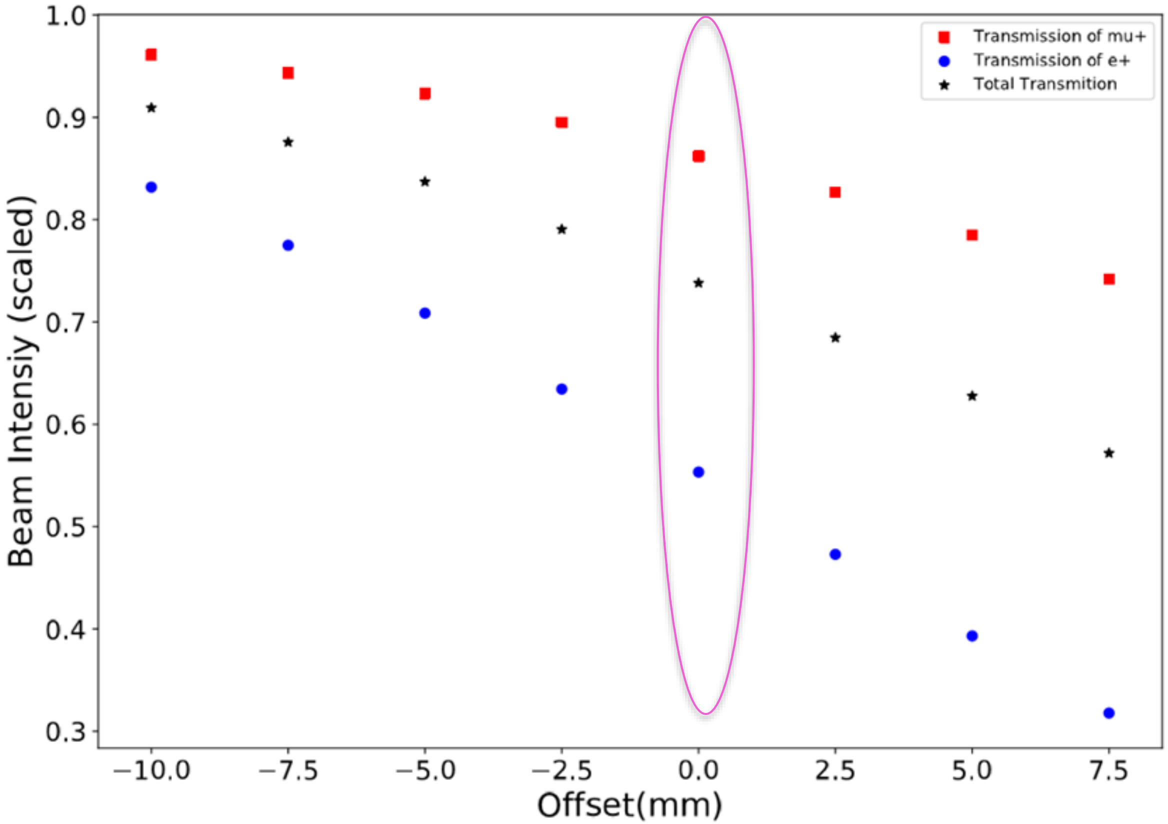
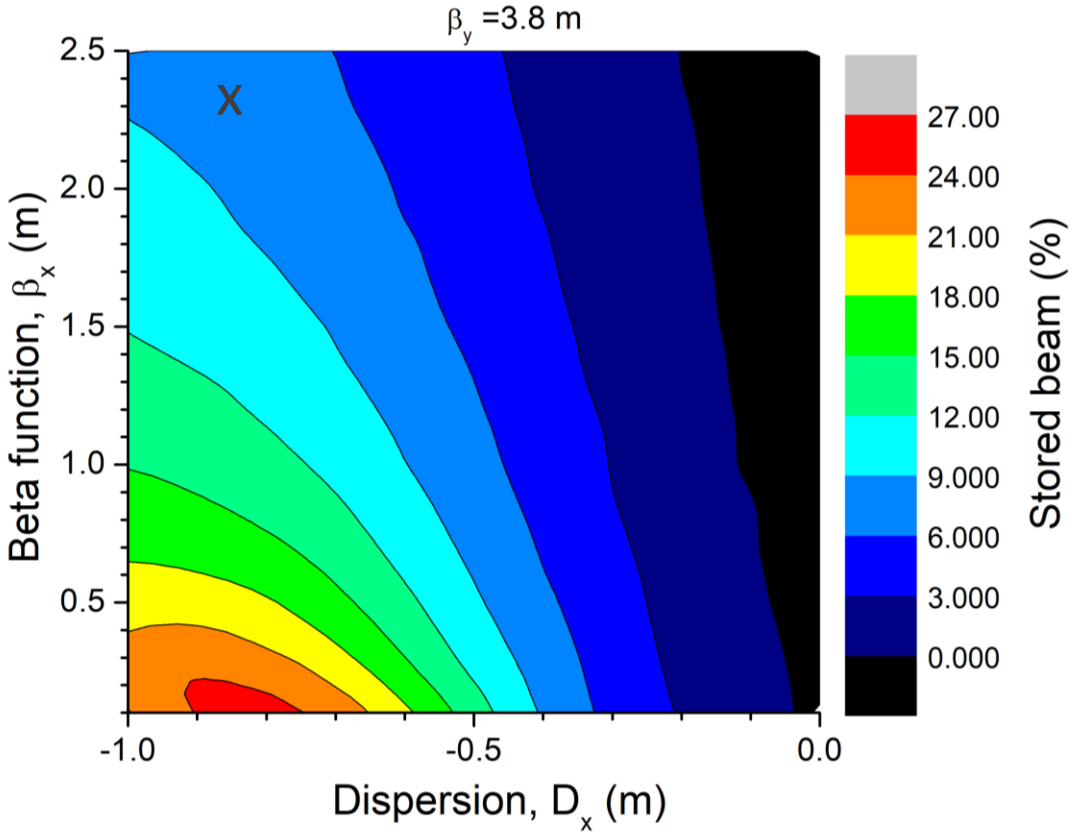
# Beam clean-up

- Muon campus beam is contaminated with target-born e+
- Simulation showed that a wedge can cut 50% of the incoming e+.



# Improvement studies: Optics adjustments

- Proper adjustments of beam optics at the wedge may improve the performance
- Practically, difficult due to both physical and hardware limitations



# Summary

- An accelerator facility to provide beams to both g-2 and Mu2e experiments has been designed and constructed at Fermilab
- The facility has been commissioned and is now in the operation phase for the Muon g-2 Experiment
- Through Fermilab's LDRD program we have been awarded a grant to design, install and test a wedge in the Fermilab Muon Campus. The system was installed and commissioned on time.
- Proof-of-principle test showed a up to 7% improvement on stored muons
- We hope to increase the improvement rate by modifying the beamline optics and upstream beam energy

# Further contributions

- Student Research

**Nick Amato**
Master's Thesis, NIU (Syphers)
May 2019
Title: Improved momentum spread for precision physics experiments using wedges

**Lauren Carver**
Fermilab Intern
Summer 2019
Title: Modeling a wedge absorber for the g-2 Experiment


**Jerzy Manczak**
Fermilab Intern
Summer 2018
Title: Modeling a wedge absorber for the Mu2e Experiment

**Joe Bradley**
Fermilab Intern
Summer 2017
Title: Material & geometry study of a wedge absorber for the g-2 Experiment

- Literature

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22**, 053501 (2019)

**Application of passive wedge absorbers for improving the performance of precision-science experiments**

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Nuclear Inst. and Methods in Physics Research, A 962 (2020) 163704

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

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Realistic modeling of a particle–matter-interaction system for controlling the momentum spread of muon beams

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# Acknowledgements


- Thanks to Mike Syphers (co-PI, LDRD), for providing help with the Monte Carlo which was used for the wedge parameter scans
- Thanks to Jim Morgan (LDRD coordinator) for monitoring the fabrication and installation process
- Thanks to Carol Johnstone & David Neuffer for optics support
- Thanks Dirk Hurd and Jesse Batko for design and engineering support and to David Peterson for wedge motion control support.
- Thanks to George Deinlein and Nathan Froemming for operations support
- Thanks to the g-2 collaboration for supporting the project!